Co-existence of 5G Mobile Service and RAS, EESS, and SRS at 31 GHz[1]

Reed Engineering

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This whitepaper addresses the coexistence of 5G mobile service in 31 GHz to 31.3 GHz spectrum with Radio Astronomy Service (RAS), Earth Exploration Satellite Service (EESS), Space Research Service (SRS) in the adjacent 31.3 to 31.8 GHz spectrum. The paper summarizes the size of the exclusion zone or protection zone for the RAS for various practical scenarios and concludes that circular exclusion zones with the radius of about 19 miles would adequately protect the RAS from 5G transmissions. Defining a suitable received power threshold for a 5G Base Station signal at the RAS receiver would facilitate harmonious coexistence between 5G mobile service and RAS. The paper also quantifies the number of 5G transmitters that can be accommodated by EESS (e.g., few hundreds to a few thousand high-power macro Base Station transmitters per 200 km^2) under worst-case interference scenarios. The analysis finds that as many as 250 simultaneously transmitting Mobile Stations in an outdoor macro cell can be supported without causing harmful interference to a RAS receiver. Many more than 250 cell-edge Mobile Stations per cell can be supported in case of outdoor and indoor small cell deployments. Furthermore, more than a million low-power small cell Base Station transmitters or Mobile Stations in a 200 square kilometer surface area can be easily supported without causing any harmful interference to an EESS receiver. The paper concludes that the FCC-proposed Out-Of-Band-Emission (OOBE) limits (e.g., -13 dBm/MHz) can adequately protect EESS and SRS in practical 5G deployment scenarios. Note that analysis carried out in this paper assumes the worst-case interference scenario, where the path between the a 5G Base Station or Mobile Station transmitter and a receiver does not have any intervening objects such as vegetation and buildings. While the interference is allowed to exceed a target interference threshold a certain percentage of time per ITU specifications, our analysis prevents interference 100% of the time[2]. Additionally, our analysis assumes a fully-loaded cellular network, resulting in the maximum amount of interference. When the EESS receiver scans occur during the night, a lightly-loaded cellular network would cause much lower interference. Hence, exclusion zones smaller than those predicted here would suffice in practice while protecting RAS, and, more 5G transmitters (i.e., Base Stations and Mobile Stations) than those predicted here can be supported in practice while protecting EESS.

[1] This paper presents an updated analysis compared to the previous version of the paper to reflect (i) two differing interpretations of the interference threshold for the EESS, (ii) a more aggressive interference threshold defined by the ITU for the EESS, (iii) more realistic assumptions about some system parameters such as the achievable attenuation in the vertical plane of a 5G Base Station antenna toward an EESS satellite, and (iv) correction of a typo in the Excel spreadsheet calculations. This new analysis reaches the same conclusion as the previous report in that it shows that practical mobile 5G networks can co-exist harmoniously with RAS and EESS.

[2] This paper presents a high-level analysis. A more accurate analysis would require detailed knowledge of the EESS systems such as orbital and scan specifics and use of a comprehensive simulation program like STK.

The whitepaper is organized as follows. Section I briefly describes interference scenario around 31 GHz. Section II summarizes the analysis approach, lists major assumptions, and identifies enhancements to the analysis approach and/or assumptions. Section III provides conclusions of the interference analysis in the case of 5G transmitters being cellular base stations. Section IV analyzes the interference scenarios in the case of 5G transmitters being mobile stations and estimates the number of simultaneously transmitting mobile stations that can be supported in the exclusion zone around a RAS receiver. Section V discusses interference mitigation techniques that further enable harmonious coexistence between 5G mobile services and RAS, EESS, and SRS.

I. Interference Scenarios around 31 GHz

The FCC is targeting the use of certain portions of the millimeter wave spectrum to facilitate and accelerate the emerging fifth-generation (5G) wireless services as part of Upper Microwave Flexible Use Service(UMFUS) [FCC_1]. UMFUS will spur innovations and benefit consumers. One of the UMFUS spectrum bands is LMDS spectrum with A and B blocks. The A Block consists of the sub bands (i) A1 band ranging from 27.50 GHz to 28.35 GHz, (ii) A2 band ranging from 29.10 GHz to 29.25 GHz, and (iii) A3 band ranging from 31.075 GHz to 31.225 GHz. The B Block consists of the B1 band ranging from 31.00 GHz to 31.075 GHz and the B2 band ranging from 31.225 GHz to 31.30 GHz. An entity owning multiple A and B blocks can create a contiguous radio channel with wide bandwidth. For example, A3, B1, and B2 blocks can be combined to create a 300 MHz wide radio channel that ranges from 31.00 GHz to 31.30 GHz. Nextlink has such contiguous spectrum in large parts of the country, covering about 30% of the U.S. population.

The spectrum band adjacent to the B2 block is from 31.3 to 31.8 GHz, which is allocated to Radio Astronomy Service (RAS), Earth Exploration Satellite Service (EESS), Space Research Service (SRS). The services in this spectrum band are passive; the receivers make observations but there are no active transmitters. The RAS receivers are radio telescopes that are terrestrial. The EESS and SRS receivers are located on satellites. Coexistence of 5G mobile services with RAS, EESS, and SRS is analyzed in this paper.

Radio astronomy has facilitated numerous fundamental astronomical advances such as the discovery of radio galaxies and the direct measurement of distances of certain external galaxies. Radio astronomical observations help improve our understanding of the Universe and help us investigate some cosmic phenomena. To enable radio astronomers to make useful astronomical observations from the Earth's surface, ITU has defined protection criterion for RAS receivers in [ITU_RA.769-2]. According to Table 1 in [ITU_RA.769-2], a RAS receiver can be considered to be protected from interference if the amount of interference is (-192 dBW) in 500 MHz bandwidth at the frequency of 31.55 GHz[3]. If 5G transmitters are located *sufficiently far away* from the RAS receiver (i.e., a radio telescope), the interference caused to the RAS receiver would be below the reference interference threshold of (-192 dBW) per 500 MHz bandwidth, leading to harmonious coexistence of RAS and 5G mobile services. A circular exclusion zone or protection zone around a RAS receiver can be defined using such reference interference threshold. The *goals of the RAS interference analysis* in this paper are to quantify (i) the size of a circular exclusion zone

[3] [ITU_RA.769-2] specifies the receive antenna gain of 0 dBi toward the interferer while specifying this interference threshold. Hence, the amount of acceptable interference is the same whether such interference is measured at the receive antenna of the RAS receiver or at the RAS receiver itself. If the actual RAS receive antenna gain happens to be -10 dBi toward the interferer, the RAS receiver can tolerate 10 dB stronger interference than the amount of interference specified by this interference threshold. Here is an excerpt from Section 1.3 of [ITU_RA.769-2]: "However, it is useful to calculate the threshold levels of interference strength for a particular value of side-lobe gain, that we choose as 0 dBi, and use in Tables 1 to 3."

around a RAS receiver such that multiple high-power 5G base stations of a cellular network surrounding such RAS receiver do not cause detrimental interference to RAS and (ii) the number of low-power 5G mobile stations that can be supported in such exclusion zone without causing detrimental interference to RAS.

The EESS helps observe and study phenomena that influence Earth and its environment. The EESS use sensors on satellites to make useful measurements of atmosphere, land, and sea [NAP_1]. These sensors can detect variations in Earth's environment under all weather conditions. Example measurements made by these sensors include (i) temperature and humidity in the atmosphere, (ii) moisture, roughness, and biomass on the land and (iii) temperature and surface wave height in the oceans. These measurements help predict weather and severe storms and improve our understanding of changes in global climate. SRS is a radio communication service, where spacecraft or other objects in space are used for scientific or technological research purposes [Bra2012]. ITU has defined protection criterion for EESS receivers in [ITU_RS.2017]. The FCC has noted in [FCC_1] that no separate protection criterion has been defined by the ITU for SRS. Hence, this paper utilizes the same protection criterion for both EESS and SRS and assumes that the EESS analysis is applicable to the SRS analysis as well. According to Table 2 in [ITU_RS.2017],ITU_SM.2092 an EESS receiver can be considered to be protected from interference if the amount of interference is (-166 dBW) in 200 MHz bandwidth[4]. If the number of simultaneously active 5G transmitters is *sufficiently small*, the cumulative interference caused to the passive EESS sensor receiver would be below the reference interference threshold of (-166 dBW) per 200 MHz bandwidth. Under these conditions, 5G mobile services and EESS and SRS can coexist without 5G mobile services causing harmful interference to EESS and SRS. The *goal of the EESS and SRS interference analysis* in this paper is to quantify the number of 5G transmitters that can be accommodated by EESS and SRS receivers such that 5G transmitters do not cause harmful interference to EESS and SRS.
The analysis focuses on the Out of Band Emission interference caused by a 5G transmitter due to the frequency vicinity of 5G and RAS/EESS systems. Since the interference protection guidelines from ITU are used as the baseline, adherence to these guidelines dictates the amount of interference that can be tolerated by a RAS/EESS receiver. The analysis carried out in the paper ensures that the interference generated by 5G transmitters and experienced by the RAS/EESS receiver stays below such interference power limit. Furthermore, receivers are often designed to operate well above the minimum-performance guidelines. Hence, once such interference limit is adhered to, the RAS/EESS receiver in practice will be able to recover the desired signal, and, receiver overload would not become a challenge.

We note that the specification of the interference threshold for RAS is unambiguous in the ITU documents such as [ITU_RA.769-2]. The receive antenna gain of 0 dBi is clearly specified in [ITU_RA.769-2], and, the amount of interference, therefore, is the same whether measured (i) at the input to the receive antenna or (ii) at the receiver itself (i.e., after the interference has passed through the receive antenna and other components of the receiving system such as a filter).

In contrast to the RAS interference specification, the specification of the interference threshold for EESS is ambiguous in our opinion when different ITU documents such as [ITU_RA.769-2], [ITU_RS.2017], and [ITU_SM.2092] are studied. Our previous report [Reed_2016] had assumed that the EESS interference is measured at the input to the receive antenna that is the first point of contact of the receiving system with interference and the signal of interest. However, it has come to our attention that the EESS interference threshold could also be interpreted to be at the input to the receiver itself. For

[4] In the previous version of this paper, we had used -163 dBW in 100 MHz bandwidth based on [ITU_SM.2092]. However, in the newer ITU requirements are more stringent per [ITS_RS.2017]. Hence, this paper uses more aggressive interference threshold of -166 dBW in 200 MHz based in newer and tighter interference requirements per [ITU_RS.2017].

example, the impact of fixed systems on EESS is analyzed in [SM.2092] using such interpretation of the interference threshold defined in [ITU_RS.1029]. We note that the newer ITU document, [ITU_RS.2017], uses the same interference determination procedure as the older ITU document [ITU_RS.1029] and is also subject to two different interpretations of the interference threshold.

To determine the correct interpretation of the interference threshold, we have communicated with multiple experts in the academia and the industry and have reached the conclusion that the EESS interference threshold being specified in the ITU documents could be interpreted to be (i) at the input to the receiver itself or (ii) at the input to the receive antenna. The first interpretation requires the interference to be much weaker (e.g., by as much as 45 dB when the receive antenna gain is 45 dBi) than the second interpretation. Some experts believe that the interference is measured at the input to the receive antenna, while others believe that the interference is measured at the input to the receiver itself. One of the ITU technical personnel, ITU-R SG 7 counselor, has conveyed to us that the interference threshold is at the input to the receiver but that his view may or may not represent an official ITU position on this subject. The details that support the second interpretation mentioned above are presented next.

ITU RS.2017 mentions the following.

> "…that surface brightness temperature, the atmospheric temperature at points along a path and absorption coefficients can be determined from measurements of the sensor antenna temperature, T_A;…"

Since the sensor antenna measurement is mentioned above, the receive antenna does seem to play a role in the performance requirements.

ITU RS.2017 further states that

> "n) that performance requirements for passive sensors can be stated in terms of measurement sensitivity, ΔT_e, and availability, measured at the satellite, assuming that degradation from other elements in the system will be small; "

The references to "the satellite" and "other elements in the system" imply that the overall system is being considered while specifying the performance requirements. Obviously, the satellite includes the receiver antenna, the receiver itself, and other elements.

[ITU_RS.2017] also mentions the following.

> "o) that the sensitivities of radiometric passive sensors are generally expressed as a temperature differential, ΔT_e, given by:

$$\Delta T_e = \alpha\, T_S / \sqrt{Bt} \qquad \mathrm{K}$$

where:

- ΔT_e: radiometric resolution (root-mean-square (r.m.s.) uncertainty in estimation of total system noise, T_s);
- α: receiver system constant;
- T_s: system noise temperature (K) (antenna temperature and receiver noise temperature);

B : spectral resolution (of spectro-radiometer) or “reference bandwidth” of a single radiometric channel (Hz);

t : sensor integration time (s);”

Note that the overall receiving system is being considered above and that the antenna temperature is explicitly mentioned in addition to the receiver noise temperature. Both the target signal and interference enter the receiving system at the receive antenna.

An approach similar to [ITU_RS.2017] is used in [ITU RA.769-2] for RAS. As mentioned earlier, compared to [ITU_RS.2017], [ITU_RA.769-2] is clearer and more explicit while specifying the location of the interference measurement. [ITU_RA.769-2] uses the receive antenna gain of 0 dBi and mentions the following:

> “The interference can also be expressed in terms of the pfd incident at the antenna, either in the total bandwidth or as a spectral pfd, *SH*, per 1 Hz of bandwidth.”

Also, [ITU_RS.769-2] says this in Footnote 3 of Table 1:

> “(3) The interference levels given are those which apply for measurements of the total power received by a single antenna.”

Additionally, [ITU_RS.769-2] says this in Footnote 2 of Table 2:

> “ (2) The interference levels given are those which apply for measurements of the total power received by a single antenna.”

The text above clearly mentions the power received by an antenna, implying that interference should be measured at the receive antenna. Both the target signal and interference enter the receiving system through the antenna.

We also note that it is quite common in the cellular communications to state the power related performance requirements using the power measurements at the antenna. For example, 3GPP, an organization that has defines 4G LTE specifications, mentions the following in Section 7.1 of TS 36.101.

> “Unless otherwise stated the receiver characteristics are specified at the antenna connector(s) of the UE. “

> “The levels of the test signal applied to each of the antenna connectors shall be as defined in the respective sections below.”

Finally, we note that defining the interference threshold at the input to the receiver antenna readily enables engineers to design the interfering transmitter without making assumptions about the receive antenna gain of all existing and future EESS systems. Even if a transmitter is designed considering all the existing EESS (which would be a challenge in itself), any future EESS cannot be guaranteed to be protected if the future EESS has different performance capabilities than existing EESS.

Due to the ambiguity of the interference threshold, we are presenting our analysis in this report with both the interpretations of the interference threshold.

II. Analysis Approach

The key steps for the RAS interference analysis are specified below.

1. Define the target received interference power level in the reference bandwidth at the RAS receiver (i.e., -192 dBW in 500 MHz[5]).
2. Calculate the Effective Isotropic Radiated Power (EIRP) of the 5G Base Station transmitter constrained by the FCC-mandated maximum Out of Band Emission (OOBE) levels[6] (i.e., -5 dBm/MHz within 10% of the channel edge and -13 dBm/MHz beyond 10% of the channel edge).
3. Consider first-tier of interference caused by high-powered macro base stations[7], receive antenna gain, carrier frequency, free-space path loss, interference threshold from Step 1, and EIRP from Step 1 to estimate the radius of the protection zone surrounding the RAS receiver.

Major parameters used in the RAS interference analysis are listed below.

- Transmit and Receive Channel Bandwidth: 300 MHz[8]
- Carrier frequency: 31.55 GHz
- Receive antenna gain of the RAS receiver toward a 5G transmitter: -10 dB[9]
- Vegetation loss is not considered in this worst-case interference analysis. Vegetation in the propagation path from a 5G transmitter to a RAS receiver would significantly weaken the interference experienced by a RAS receiver[10].
- Atmospheric absorption loss is typically 0.1 dB per km around 30 GHz [ITU_Atmosphere] [FCC_Atmosphere] and is not considered in the RAS analysis, because relatively short distances in 5G cells imply relatively small additional propagation path loss. Note that propagation toward the horizon and longer distances would result in a non-negligible absorption loss.
- Shadow fading caused by obstructions is not considered in this worst-case interference analysis and could significantly weaken the interference from 5G transmitters. Obstructions such as buildings can cause attenuation of more than 20 dB (e.g., 40 dB to 80 dB due to the construction materials of a building such as bricks, concrete, Etc.).[11]
- Line-of-Sight (LOS) propagation is assumed between a 5G transmitter and a RAS receiver in this worst-case interference analysis. Non-LOS (NLOS) propagation would significantly weaken the interference from 5G transmitters. The propagation path loss exponent “n” of about 2 is appropriate for LOS propagation and 4.5 is appropriate for NLOS propagation around 28 GHz. A larger n corresponds to larger path loss[12].

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[5] See [ITU_RA.769-2].

[6] See [FCC_1].

[7] A typical receiver located in overlapping cell-edge coverage areas of base stations would get interference from about three Base Station transmitters. In practice, RF planning and design can reduce the number of first-tier of interferers from three to zero if needed. The use of three transmitters is a way of modeling an aggregate interference scenario as opposed to a single-transmitter scenario.

[8] The 5G transmitter bandwidth is 300 MHz when all of A3 band (31.075-31.225 GHz), B1 band (31.00-31.075 GHz), and B2 band (31.225-31.30 GHz) are used.

[9] See [ITU_RA.769-2]. The gain is specified to be in the range from 32 dBi to -10 dBi. Due to the pointing of the RAS receive antenna relative to the transmit antennas of cellular base stations, -10 dBi gain is considered to be more practical.

[10] A 15 m row of pine trees has been found to cause 24.8 dB attenuation at 35 GHz. See [Kut2016] for details.

[11] See [Kha2011] for details.

[12] See [Rap2015] for details.

- Beamforming related parameters:
  - Radio resources undergoing user-specific beamforming: 75% (i.e., no beamforming for 25% of resources carrying overhead such as Reference Signals used for cell acquisition)
  - Beamforming attenuation toward a RAS receiver (e.g., due to traditional RF design optimization techniques such as antenna down-tilting and azimuth changes and/or null-steering technique implemented by an antenna): -40 dB (as seen from Figure 1, for example)[13]
  - Attenuation of overhead signals toward a RAS receiver: -15 dB[14]. Note that a typical Base Station antenna is down-tilted by few degrees relative to horizon and results in attenuation toward horizon. Since the antenna beam width is quite small (e.g., 5° to 15°) in the vertical plane, there is sharp attenuation in the vertical plane away from the antenna boresight.
- Small cell related parameters:
  - Small cell EIRP: 37 dBm[15] (or 5 W) in 300 MHz.
  - In-band to out-of-band power ratio[16]: 60 dB
  - OOBE: -48 dBm per MHz[17]

[13] Such assumption is conservative. Three dimensional arrays can also provide significantly better sidelobe reduction, although the third dimension will not reduce beam width directly. In addition to Figure 1, also see [Bak2010] for more examples and with realistic hardware impairments.

[14] This is an example value. Examples of 2-D array beam pattern properties can be found in [Bak2010]. An RF design may decide to reduce the sector size or even eliminate a sector facing the RAS receiver.

[15] A small cell aims for a much smaller footprint compared to macro cells. This power level is an example power level and small cells in practice would have different power levels. For example, the power level can be 250 mW for a local area BS and 6.3 W for a medium range BS. See Tables 3-1 and 3-2 in [Sma2017] for more details. See also [Kha2011], [Pug2015], and [Gim2016].

[16] This is based on the FCC-allowed transmit power of 75 dBm per 100 MHz (i.e., 55 dBm/MHz in-band transmission power) and OOBE of -5 dBm/MHz just outside the channel edge. These FCC-proposed power levels imply that the in-band power to out-of-band power ratio is 55 – (-5) = 60 dB. Potential waveforms being discussed for 5G include Filter Bank Multi Carrier (FBMC) and Universal Filtered Multicarrier (UFMC). These waveforms and suitable baseband and RF filtering can help achieve this level of out of band rejection. See [Anr2016] and [Bal20007].

[17] OOBE in 300 MHz bandwidth is (37 dBm – 60 dB = -23 dBm) or (-23 dBm – $10*\log_{10}(300)$ = -48 dBm/MHz).

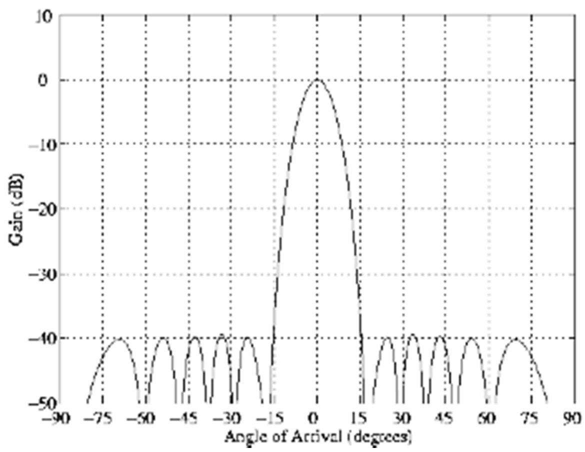

Figure 1. Theoretical uniform linear array with Hanning window applied across 16 elements.
(Additional elements can be used to narrow the array beam and reduce sidelobe levels with appropriate weighting.)

The key steps for the EESS interference analysis are specified below[18].

1. Define the target received interference power level in the reference bandwidth at the EESS receiver (i.e., -166 dBW in 200 MHz bandwidth).
2. Calculate the Effective Isotropic Radiated Power (EIRP) of the 5G Base Station transmitter using FCC-permitted Out of Band Emission (OOBE) levels (i.e., -5 dBm/MHz within 10% of the channel edge and -13 dBm/MHz beyond 10% of the channel edge).
3. Determine free-space path loss between the 5G transmitter and the EESS satellite receiver using carrier frequency, and satellite altitude. Note that this path loss is between the transmit antenna of a 5G transmitter and the receive antenna of an EESS receiver.
4. Calculate the power received at the satellite from a single 5G transmitter. This power is estimated (i) at the input to the receive antenna in case of Scenario A and (ii) at the input to the receiver in case of Scenario B.
5. Calculate the maximum allowed interference power in the target receiver bandwidth based on reference interference threshold from Step 1 and target receiver bandwidth.
6. Consider the received power from a single transmitter from Step 4 and the maximum allowed interference power from Step 5 to estimate the number of simultaneous transmitters that can be supported.

Major parameters used in the EESS interference analysis are listed below.

- Transmit and Receive Channel Bandwidth: 300 MHz
- Carrier frequency: 31.55 GHz
- Receive antenna gain of the EESS receiver toward a 5G transmitter: 45 dB[19]
- Satellite altitude: 850 km[20]
- Surface area[21] on the Earth covered by the EESS satellite's sensor pixel: 201 km^2

[18] See Appendix A for numerical calculations that are based on these steps.

[19] See Section 9 in ITU-R SM.2092.

[20] See Section 9 in ITU-R SM.2092.

[21] See Section 9 in ITU-R SM.2092.

- Atmospheric absorption loss for the EESS analysis is assumed to be 1 dB for a satellite in the nadir position. Such loss is typically 0.1 dB per km around 30 GHz at the sea level [ITU_Atmosphere] [FCC_Atmosphere] and is considered here due to large distances. Compared to the sea level, the oxygen level drops to 50% at the altitude of 18,000 ft or 5.5 km and 33% at the altitude of 29,000 ft or 8.8 km. While the oxygen density reduces as the altitude increases, the length of the path that the signal travels through increases. Oxygen would typically be present within the troposphere that spans up to the altitude of 12 km. Considering all these factors, the overall absorption loss due to oxygen in the atmosphere could be estimated to be 1 dB for the EESS in the nadir direction. Note that the entire atmosphere with varying densities of oxygen and water vapor would be traversed by the interfering signal emanating from a 5G transmitter. A satellite at a non-nadir position would experience a larger atmospheric absorption loss due to relatively longer propagation path through the earth's atmosphere.
- Beamforming related parameters:
    - Radio resources undergoing user-specific beamforming: 75% (i.e., no beamforming for 25% of resources carrying overhead such as Reference Signals)
    - Beamforming attenuation toward an EESS receiver: -40 dB[22]
    - Attenuation of overhead signals toward an EESS receiver: -30 dB[23]

III. Summary of the Interference Analysis: 5G Base Stations as Transmitters

A given RAS receiver may see interference from three base stations for a traditional macro cellular deployment with 120° sectorization. Table 1 summarizes the results of the RAS analysis when 3 Base Station transmitters are simultaneously active and causing interference to a RAS receiver. 5G would also deploy numerous small cells. The cases for 100, 500, and 1000 small cell transmitters are also shown in Table 1.

[22] The beamforming attenuation levels used in this case of EESS receivers are the same as those used for the RAS interference analysis. Since a RAS receiver is terrestrial, while an EESS receiver is on a satellite, higher attenuation levels are expected for an EESS receiver and actual interference experienced by an EESS receiver would be less than the amount of interference assumed in this analysis.

[23] See the following for feasibility of antenna attenuations. 1. http://www.raymaps.com/index.php/antenna-radiation-pattern-and-antenna-tilt/ 2. https://files.acrobat.com/a/preview/1322a8b2-2b75-4294-b0c4-fc8f12b706cb (pages 77-78for the case of a 30-40 GHz horn with a 30 dB attenuation off boresight).

Table 1. Exclusion Zone around a RAS Receiver for Multiple Simultaneous 5G Base Station Transmitters

Scenario	RAS Receiver Channel Bandwidth (MHz)	Maximum Allowed Interference Power in Receive Bandwidth (dBm)	Effective OOBE EIRP of a 5G Transmitter in Receive Bandwidth (dBm)	Radius of an Exclusion Zone (km)	Radius of an Exclusion Zone (miles)
3 Macro Cells (beamforming, 5G RF optimization)	200	-165.98	-8.43	31.3	19.4
	300	-164.22	-7.36	28.9	17.9
	500	-162.00	-5.79	26.8	16.6
100 Small Cells (beamforming and RF optimization)	500	-162.00	-41.77	2.4	1.5
1,000 Small Cells (beamforming and RF optimization)	500	-162.00	-41.77	7.8	4.8
10,000 Small Cells (beamforming and RF optimization)	500	-162.00	-41.77	24.6	15.3

Based on the results summarized in Table 1, ***an exclusion zone with a radius of about 31 km or 19 miles around a RAS receiver would adequately protect a RAS receiver from a 5G mobile network***. ***We further note that smaller exclusion zones would be adequate in practice due to the worst-case interference scenario assumed in the analysis.*** Note that analysis carried out here assumes the worst-case interference scenario, where the path between the a 5G transmitter and a RAS receiver does not have any intervening objects such as vegetation and buildings. In practice, these objects would significantly weaken the actual interference experienced by a RAS receiver. For example, interference from a 5G transmitter could easily attenuate by 20 dB to 30 dB (i.e., 100 to 1000 times weaker) due to the presence of such intervening objects. Hence, exclusion zones smaller than those predicted here would suffice in practice. Additionally, RAS receivers are often located away from population centers, the requirement of such exclusion zones can be met easily.

Table 2 summarizes the results of the EESS analysis for 5G transmitters for Scenario A.

Table 2. Supportable 5G Transmitters while Protecting an EESS Receiver for Scenario A

Scenario	EESS Receiver Channel Bandwidth (MHz)	Maximum Allowed Interference Power in Receive Bandwidth (dBm)[24]	Effective OOBE EIRP of a Single 5G Transmitter in Receive Bandwidth (dBm)	Interference Power in Receive Bandwidth due to a Single Transmitter (dBm)	Maximum Number of Transmitters in 201 km^2 Satellite Beam	Implied Cell Radius of a Hexagonal Cell (m)[25]
Macro Cells (beamforming, 5G RF optimization)	200	-136	-22.33	-204.34	6,818,497	3.4
	300	-134	-21.26	-203.27	8,000,872	3.19
	500	-132	-19.69	-201.70	9,289,574	2.94
Small Cells (beamforming and RF optimization)	200	-136	-59.65	-241.66	36.8 billion	0.05
	300	-134	-57.89	-239.90	36.8 billion	0.05
	500	-132	-55.67	-237.68	36.8 billion	0.05

Based on the results summarized in Table 2 for Scenario A, ***about 6.8 million to 9.3 million high-power Base Station transmitters in about 200 square kilometer surface area can be easily supported without causing any harmful interference to an EESS receiver***. **Furthermore, *about 36.8 billion low-power small cell Base Station transmitters in 200 square kilometer surface area can be easily supported without causing any harmful interference to an EESS receiver.*[26]**

Table 3 summarizes the results of the EESS analysis for 5G transmitters for Scenario B.

[24] Compared to the previous version of the report, this interference threshold is 6 dB lower, reducing the total number of supportable 5G transmitters if no other parameters change.

[25] The implied cell radius is specified here merely to provide an idea of the density of supportable 5G base station deployments and should not be viewed as a radius of an actual cell, especially when supportable deployments are ultra-dense.

[26] In case of the macro cells, the OOBE EIRP has a non-linear roll-off with receive bandwidth due to different attenuation levels within the receive bandwidth. In case of fixed 5 W small cells, the OOBE has a linear relationship with the receive bandwidth, making the number of supportable small cell BS transmitters independent of the receive bandwidth.

Table 3. Supportable 5G Transmitters while Protecting an EESS Receiver for Scenario B

Scenario	EESS Receiver Channel Bandwidth (MHz)	Maximum Allowed Interference Power in Receive Bandwidth (dBm)	Effective OOBE EIRP of a Single 5G Transmitter in Receive Bandwidth (dBm)	Interference Power in Receive Bandwidth due to a Single Transmitter (dBm)	Maximum Number of Transmitters in 201 km^2 Satellite Beam	Implied Cell Radius of a Hexagonal Cell (m)[27]
Macro Cells (beamforming, 5G RF optimization)	200	-136	-22.33	-159.34	215	600
	300	-134	-21.26	-158.27	253	553
	500	-132	-19.69	-156.70	293	514
Small Cells (beamforming and RF optimization)	200	-136	-59.65	-196.66	1.2 million	8
	300	-134	-57.89	-194.90	1.2 million	8
	500	-132	-55.67	-192.68	1.2 million	8

Based on the results summarized in Table 3 for Scenario B, ***about 215 to 293 high-power Base Station transmitters in about 200 square kilometer surface area can be easily supported without causing any harmful interference to an EESS receiver***. **Furthermore*, about 1.2 million low-power small cell Base Station transmitters in 200 square kilometer surface area can be easily supported without causing any harmful interference to an EESS receiver. Since 5G deployments in the millimeter wave (mmW) spectrum are expected be primarily small cells, an ultra-dense 5G deployment with an outdoor base station every (2 x 8 m = 16 m) can be easily supported without causing interference to EESS receivers. Many more indoor small cell base stations can be supported due to the additional penetration loss (e.g., as high as 40 dB) experienced by 5G signals from an indoor 5G base station to an EESS receiver.***

We also note that our analysis meets the interference threshold criterion 100% of the time. In practice, EESS scans occur during specific times and when such scans occur during the night, 5G transmitters are likely to cause much less interference, because the loading in the cellular network and subsequently the total transmit power from the cellular network would be much less than the fully-loaded cellular network assumed in our worst-case interference analysis.

Table 4 summarizes the results of the EESS analysis for 5G transmitters for Scenario B, when the 5G transmitter specifications exceed the FCC-allowed OOBE limits by different amounts.

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[27] The implied cell radius is specified here merely to provide an idea of the density of supportable 5G base station deployments and should not be viewed as a radius of an actual cell, especially when supportable deployments are ultra-dense.

Table 4. Supportable 5G Transmitters while Protecting an EESS Receiver for Scenario B (5G Transmitters Outperforming FCC OOBE Limits)

Scenario	Amount by which 5G Tx Outperforms FCC OOBE Limits (dB)	Maximum Allowed Interference Power in Receive Bandwidth (dBm)	Effective OOBE EIRP of a Single 5G Transmitter in Receive Bandwidth (dBm)	Interference Power in Receive Bandwidth due to a Single Transmitter (dBm)	Maximum Number of Transmitters in 201 km^2 Satellite Beam	Implied Cell Radius of a Hexagonal Cell (m)[28]
Macro Cells (beamforming, 5G RF optimization, 300 MHz bandwidth)	5	-136	-26.26	-163.27	800	311
	10	-134	-31.26	-168.27	2530	175
	15	-132	-36.26	-173.27	8000	98

Based on the results summarized in Table 4 for Scenario B, ***about 800 to 8,000 high-power Base Station transmitters in about 200 square kilometer surface area can be easily supported without causing any harmful interference to an EESS receiver when a 5G transmitter outperforms FCC OOBE specifications***.

Mobile Stations have much less power than macro Base Stations and even small cells. For example, while a small cell may have 37 dBm maximum transmit power, a Mobile Station typically has the maximum transmit power of only 23 dBm. In other words, the Mobile Station's maximum transmit power is 14 dB lower than the small cell transmit power. This implies that the Mobile Station would be transmitting at least 25 times weaker signal than a small cell. Furthermore, the use of power control and distribution of Mobile Stations in a given cell would lead to the actual transmit power of the Mobile Station less than 23 dBm. Hence, many more than a million (e.g., more than 25 million) Mobile Stations can be simultaneously supported in a 200 square kilometer area.

Additionally, we note that more 5G transmitters can be supported than the number of transmitters predicted here due to the worst-case interference scenario assumed in the analysis. More specifically, any intervening objects such as buildings and vegetation between a 5G transmitter and an EESS receiver would significantly weaken the interference experienced by the EESS receiver.

[28] The implied cell radius is specified here merely to provide an idea of the density of supportable 5G base station deployments and should not be viewed as a radius of an actual cell, especially when supportable deployments are ultra-dense.

IV. Summary of the RAS Interference Analysis: 5G Mobile Stations as Transmitters

The radius of the exclusion zone around a RAS receiver specified in Section III assumes that the worst-case interference is caused by a high-power Base Station (BS) transmitter and not by multiple low-powered Mobile Station (MS) transmitters. The analysis carried out in this Appendix determines the number of MSs that would generate the same amount of interference as a full-power BS. As long as practical deployments involve fewer simultaneously transmitting MSs than the number of supportable MSs predicted by the analysis, the exclusion zone around a RAS receiver estimated for BS transmitters would still be valid and 5G Base Stations or Mobile Stations can co-exist harmoniously with RAS.

High-Level Analysis Approach

The analysis aims to answer this question: How many Mobile Station transmitters are equivalent to 1 full-power Base Station transmitter?

1. Calculate the amount of interference generated at a RAS receiver (e.g., x mW) due to full-power transmission from one BS.
2. Calculate the amount of interference generated at a RAS receiver (e.g., y mW) due to power-controlled transmission from one MS located on the cell-edge of a 5G sector between the RAS and BS.
3. Estimate the number of simultaneous MSs on the cell-edge of a 5G sector within this region (x/y).

Assumptions

- 5G link budget (i.e., maximum allowable path loss): 129 dB
- 5G cell-edge data rate: 50 Mbps
- OOBE EIRP of an MS transmitter: -27.8 dBm (corresponding to 43 dBm in-band EIRP of the MS and out-of-band to in-band attenuation of 60 dB)

***The analysis finds that about 250 simultaneously transmitting Mobile Stations in a macro cell can be supported at the cell-edge*, which is about 2 km from the BS and 34 km from the RAS as shown in Figure 2 below.** In practice, a 5G cell may be much smaller than 2 km depending upon the deployment scenario. Note that the exclusion zone can be enlarged to accommodate even more MSs (see Table 5 below) and the impact of the MSs can be entirely prevented from operating inside the exclusion zone by turning off the sector toward the RAS receiver. Many more that 250 cell-edge Mobile Stations can be supported in case of outdoor and indoor small cell deployments. Furthermore, the use of power control and distribution of Mobile Stations in a given cell would lead to the actual transmit power of the Mobile Station much less than the maximum transmit power assumed here. Note that analysis carried out here assumes the worst-case interference scenario, where the path between the a 5G Mobile Station transmitter and a RAS receiver does not have any intervening objects such as vegetation and buildings. In practice, these objects would significantly weaken the actual interference experienced by a RAS receiver. For example, interference from a 5G Mobile Station transmitter could easily attenuate by 20 dB to 30 dB (i.e., 100 to 1000 times weaker) due to the presence of such intervening objects. Hence, 100 times more Mobile Stations (e.g., 25,000 instead of 250) can potentially be supported in practice.

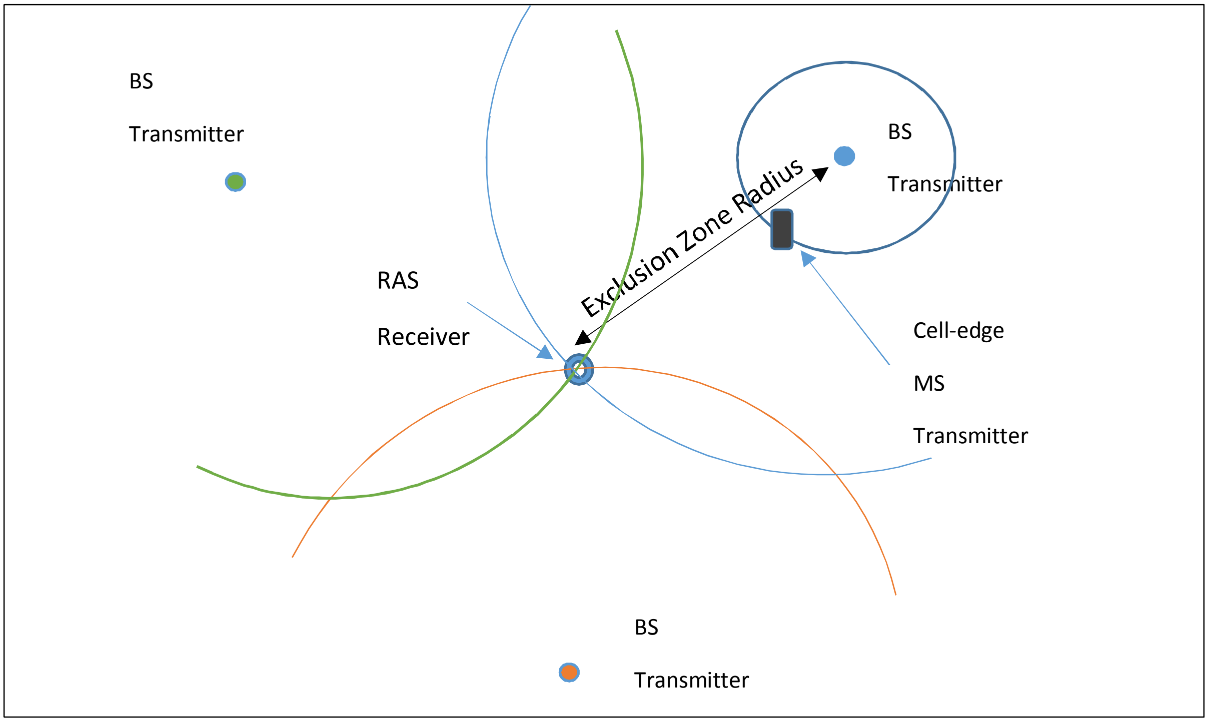

Figure 2. 5G Deployment Scenario for RAS Exclusion Zone

Table 5. Influence of the Exclusion Zone Size on Supportable MSs

Radius of the Exclusion Zone (km)	**Number of Simultaneous Cell-edge MSs**
36	**255**
40	**320**
50	**510**

In today's network, tens of devices are scheduled for uplink transmission simultaneously. Hence, considering that about 250 cell-edge MSs can be simultaneously supported without any transmit beamforming in the uplink, many more than 250 MSs distributed across a macro sector can be supported with transmit beamforming in the uplink.

V. Interference Mitigation Techniques

Analysis in this paper is carried out using worst-case interference scenarios. There are several factors that would mitigate interference in practice, leading to requirements of smaller protection zones around RAS receivers and an even greater number of supportable 5G transmitters while protecting EESS/SRS receivers. For example, 5G is considering several candidate waveforms (e.g., Universal Filtered Multi Carrier (UFMC) and Filter Bank Multi Carrier (FBMC)) as an alternative to currently used Orthogonal Frequency Division Multiplexing (OFDM)-based waveform in 4G LTE networks. Such waveforms are expected to reduce OOBE, reducing the amount of interference caused to adjacent frequency bands[29].

While the analysis has assumed 40 dB reduction toward a RAS receiver, larger attenuation would be possible to achieve due to massive MIMO in the mmW spectrum[30]. In general, it is easier to achieve very deep nulls using an antenna array than it is to achieve a high-gain beam. Null steering can be built into the array algorithms.

The analysis is carried out for high-powered macro and micro Base Station transmitters and outdoor small cells. Indoor small cells will significantly attenuate 5G signals (e.g., by 15 dB to 20 dB) and reduce interference to RAS, EESS, and SRS receivers. Beamforming implemented at the device would further reduce the amount of 5G interference.

The analysis has assumed free-space path loss between the transmitter and the receiver. In practice, vegetation and shadow fading due to the natural obstructions and/or man-made structures would further weaken 5G signals by the time these signals reach the receiver. Vegetation attenuation can be drastic with foliage losses 1.3 – 2.0 dB/m for the first 30m of vegetation[31].

Sensor based approaches can also be used to ensure that the region of a sensitive device is not being interfered with. Such techniques are being used in the 3.55 GHz CBRS band and a simplified version could, if needed, be applied to 31 GHz. In particular, due to relatively deterministic scan patterns of EESS could facilitate such coordination between EESS and 5G if needed.

Finally, there is more to interference mitigation than just the physical layer. 5G will be composed of heterogeneous systems dynamically operating across and in conjunction with different bands. Hence, if the network knows the position of the user equipment, it can transfer the communications link to another band as needed.

[29] See [Anr2016] and [Bal2007] for more details.

[30] See [Kut2016] for more details.

[31] See [Sch1988] for more details.

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